$2p$ decays of ^{12}O excited states

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In ^{12}O, the 2^+ state whose dominant configuration is ^{10}C$(2^+) \times \pi$ $(sd)^2_0$ should be populated in neutron removal from ^{13}O, and its primary decay is via $2p$ emission to the 2^+ state of ^{10}C. My calculations predict that most of the events near $E_{2p} = 3.5$ MeV in a recent $^{12}\text{O} \rightarrow {}^{10}\text{C} + 2p$ experiment represent decays to the 2^+ state.

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I. INTRODUCTION

Webb *et al.* [1] recently reported results of an investigation of two-proton decays of ^{12}O, which was formed in $1n$ removal from ^{13}O. Their $^{10}\text{C} + 2p$ spectrum contained three prominent peaks, at approximate energies of $E_{2p} = 1.7$, 3.8, and 6.5 MeV. The second of these gave clear indications of at least two contributions, a narrow one at 3.817(18) MeV and a much broader shoulder near 3.52(7) MeV. Their results are listed in Table I.

II. CALCULATIONS AND ANALYSIS

Earlier, I had investigated the expected relative population of 0^+ and 2^+ states in ^{12}O in $1n$ removal from ^{13}O [2]. The relevant excitation energy range contains seven expected states—three 0^+ (only two of which are known) and four 2^+ states (only one of which was known prior to the work of Webb *et al.*). These are listed in Table II, along with their estimated $1n$ removal spectroscopic factors. The expected energies [2] are only approximate and were obtained using a combination of weak coupling and a simple $(sd)^2$ shell-model calculation. Webb *et al.* attributed the peak at 6.5 MeV to decay of a 2^+ (presumably my $2_4{}^+$ state) state to the ground state (g.s.) of ^{10}C.

As part of their analysis of $^{12}\text{O} \rightarrow {}^{10}\text{C} + 2p$ events, Webb *et al.* obtained a refined value for the g.s. of ^{11}N. The energy and width of this resonance have varied quite a bit over the years. The reported energy in different experiments [3–8] has varied from 1.27 [3] to 1.63 [6] MeV, with the width varying from 0.24(24) [7] to 1.44(2) [3] MeV. Theoretical resonance energies [9–12] span a similar range, but calculated widths are all about 0.8 MeV or larger. The suggested value of Webb *et al.* is $E = 1.378(15)$, $\Gamma = 0.780(10)$, both in MeV. Long ago, Sherr and I predicted an energy and width of 1.35(7) and 0.87(10) MeV, respectively, by using a potential model and mirror symmetry for the ^{11}Be/^{11}N pair [9]. Somewhat later, I suggested adopting as a global average of experimental results the values $E = 1.41(10)$ and $\Gamma = 0.78(10)$ MeV [13]. This energy differed from the compiled value [8], but the difference was less than $2\,\sigma$. These are listed in Table III, along with two compiled values [8,14].

If the shoulder in the $^{12}\text{O} \rightarrow {}^{10}\text{C} + 2p$ spectrum at $E_{2p} = 3.5$ MeV is all due to the excited 0^+ state, its width of 0.98(18) MeV is close to that predicted [15] of 0.85(15) MeV (Table IV). However, its relative strength is very much larger than expected [2], which is only about 20% of the g.s. Webb *et al.* suggested that some of the events at this energy may arise from decay of the higher 2^+ state to the 2^+ state of ^{10}C. Constraining the energy and width to agree with those of the 6.5-MeV peak provided a branching ratio 2^+/g.s. of 0.27, but left about 60% of the shoulder as belonging to the excited 0^+. Here, I explore another possibility, viz. the decay of another 2^+ state to the 2^+ of ^{10}C. This is the 2^+ state whose dominant structure is ^{10}C$(2^+) \times \pi$ $(sd)^2_0$, which I have called $2_2{}^+$. This state should be relatively strong in $1n$ removal from ^{13}O and

TABLE I. Results of Webb *et al.* for ^{12}O (energies and widths in MeV).

J^π [a]	E_{2p}	E_x	Γ	σ (mb)
$0_1{}^+$	1.718(15)	0	0.051(19)	1.2(2)
$(0_2{}^+)$	3.519(67)	1.801(67)	0.980(182)	3.3(10)
$2_1{}^+$	3.817(18)	2.099(18)	0.155(15)	2.1(5)
$2_2{}^+$	6.493(17)	4.775(17)	0.754(25)	3.5(9)
$2_2{}^+$	6.493(17)	4.775(17)	0.754(25)	4.8(12) [b]

[a] Labeling of Webb *et al.*
[b] If 0.27 of the 6.493-MeV yield decays to the 2^+ of ^{10}C.

TABLE II. Expected states of ^{12}O and their spectroscopic factors for $1n$ removal from ^{13}O.

State [a]	E_x (MeV) [b]	Dominant configuration	S [b]
0_1	0.0	$\pi\,(sd)^2_0$	0.60
0_2	1.6	p shell	0.10
0_3	4.8	Second $\pi\,(sd)^2_0$	v. small
2_1	2.0	π $(sd)^2_2$	0.36
2_2	4.0	^{10}C$(2) \times \pi$ $(sd)^2_0$	0.43 [c]
2_3	4.7	Second π $(sd)^2_2$	v. small
2_4	5.5	p shell	1.46

[a] My labeling.
[b] Reference [2], unless noted otherwise.
[c] Present.

TABLE III. Properties of ^{11}N (g.s.) from various sources.

Year	Source	E	Γ	Ref.
1999	Potential model calc.	1.35(7)	0.87(10)	[9]
2012	Experimental average	1.41(10)	0.78(10)	[13]
2012	Compilation	1.49(6)	0.83(3)	[8]
2017	Mass evaluation	1.32(5)	0.83(3)	[14]
2019	$^{12}\mathrm{O} \rightarrow {}^{10}\mathrm{C} + 2p$	1.378(15)	0.78(1)	[1]

should have weak g.s. decays. Also, considering the proximity of the various expected 2^+ states, some mixing is inevitable.

Throughout the analysis, I use mirror symmetry for the pairs ^{13}B/^{13}O, ^{12}O/^{12}Be, ^{11}N/^{11}Be, and ^{10}C/^{10}Be. The dominant structure of the g.s. of ^{13}B is

$$^{13}\mathrm{B(g.s.)} = \mathrm{A}\,^{11}\mathrm{B}_{1p}(\mathrm{g.s.}) \times \nu(\mathrm{sd})^2_0 + \mathrm{B}\,^{13}\mathrm{B}_{1\mathrm{p}}(\mathrm{g.s.}).$$

Estimates of A^2 range from 0.21 to 0.33 [16–18]. For present purposes, I use $\mathrm{A}^2 = 0.25$. The 2^+ state of ^{12}Be with configuration $^{10}\mathrm{Be}(2^+) \times \nu\ (\mathrm{sd})^2_0$ will have a spectroscopic factor for proton removal from ^{13}B of $S = \mathrm{A}^2\ \mathrm{S}(^{11}\mathrm{B}_{1\mathrm{p}}\ (\mathrm{g.s.}) \rightarrow {}^{10}\mathrm{Be}_{1\mathrm{p}}\ (2^+))$, which gives $S = 0.43$, using the p-shell value of $S = 1.71$ [19] for ^{11}B to ^{10}Be(2^+). By mirror symmetry, this is also the S for neutron removal from ^{13}O to the state labeled 2_2 in Table II.

For $2 \rightarrow 0$ decays, sequential decay in which one nucleon has $\ell = 0$ should prevail over simultaneous $2p$ decay; but for $2 \rightarrow 2$ and $0 \rightarrow 0$ decays via $L = 0$, simultaneous decay will compete favorably with sequential. (Here and elsewhere, I use lower-case ℓ for a single nucleon and capital L for 2 (or more) nucleons.) I have calculated the expected widths of all the relevant states. These are listed in Table IV, along with previous values for some states [15,20–22]. From earlier work, if the first 2^+ state is at 2.1 MeV, its predicted width is 122 keV for sequential decay through the ^{11}N(g.s.) and 18 keV for decay through the $1/2^-$, to be compared with the reported experimental width of 155(15) keV. For a pure $^{10}\mathrm{C}(2^+) \times (\mathrm{sd})^2$ state to decay to the 2^+ of ^{10}C, the expected width for simultaneous $2p$ decay is 0.96 MeV. Of course, this value could be reduced if the state contains other components.

TABLE IV. Calculated widths (MeV) in ^{12}O.

^{12}O state	$\mathrm{E_x}$	^{10}C state	Process	Γ_{calc}	Ref.	Γ_{exp}
g.s.	0	g.s.	sim	0.031(3)	[21]	0.051(19)
			seq	0.058	[20]	
0_2	1.80	g.s.	seq	0.85(15)	[15]	(0.980(182))
2_1	2.1	g.s.	seq	0.140	[22], present	0.155(15)
2_2		g.s.	seq	0.33	present	
		2^+	sim	0.96	present	0.98?
2_4		g.s.	seq	0.38	present	0.754(25)
			sim	0.053	present	
		2^+	sim	0.35	present	

If the g.s. cross section of 1.2(2) mb is correct, and my spectroscopic factors are approximately correct, the second 0^+ state should have $\sigma = 0.23(4)$ mb, so that about 3(1) mb of the cross section for this shoulder is from other sources. If a spectroscopic factor of 0.36 corresponds to $\sigma = 2.1(5)$ mb for the first 2^+, then $S = 0.43$ would correspond to $\sigma = 2.5(6)$ mb for my second 2^+. If all these events lead to decay to the 2^+ of ^{10}C, then this leaves about 0.5 mb (with a large uncertainty) of the shoulder yield to correspond to decay of ${2_4}^+$ to 2^+, to be compared to 1.3(8) mb suggested for this decay by Webb *et al.* Some g.s. decays from 2_2 would improve the agreement. For example, if 25% goes to the g.s. (Table IV), then the second 2^+ state would account for 1.9(5) mb in the shoulder, leaving about 1.1 mb for ${2_4}^+$. If the two relevant 2^+ states are approximately degenerate, then it might be difficult to distinguish decays from them. Perhaps the somewhat different predicted widths (Table IV) might be useful in this regard.

III. CONCLUSION

In summary, my calculations predict that most of the events near 3.5 MeV in the $^{12}\mathrm{O} \rightarrow {}^{10}\mathrm{C} + 2p$ spectrum will be accompanied by a $^{10}\mathrm{C}\,\gamma$ ray. Looking for these coincident gammas would seem to be an important experiment.

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